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Comparative Study on Cooling Performance of Two PCM-Assisted EAHEs and Traditional EAHE

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Abstract. It is well known that the sensible heat storage/release process is accompanied by significant changes in the temperature of storage medium. However, this feature of the sensible heat storage medium, namely soil, is unfavorable to fully exert the potential of traditional EAHE. To overcome this deficiency, two phase change material(PCM)-assisted EAHEs are proposed, one is the hollow cylindrical PCM-assisted EAHE and the other is the cylindrical PCM-assisted EAHE. In order to investigate the actual cooling performance of these novel systems in summer, a three-dimensional numerical model based on the effective heat capacity method is established by FLUENT 16.0. And the calculation results of this model have been validated in previous studies. Then, under the condition of equal air volume, a comparative study between these PCM-assisted EAHEs and the Traditional EAHE has been conducted to evaluate their cooling performance under the high-temperature meteorological conditions in Chongqing (China). The results indicate that the cooling performance of these PCM-assisted EAHE systems has been significantly improved when compared with the Traditional EAHE. And in terms of the improvement on cooling performance, the cylindrical PCM-assisted EAHE performs better than the hollow cylindrical PCM-assisted EAHE. More specifically, the total cooling capacities contributed by the hollow cylindrical PCM-assisted EAHE and cylindrical PCM-assisted EAHE have been respectively improved by 17.68% and 20.05% during the 20-days investigated period. The excellent performance of cylindrical PCM-assisted EAHE ultimately limits the temperature fluctuation of fresh air introduced by this novel system to less than 1°C.

1 Introduction

Generally, the shallowly buried air pipes are the key component of an earth-air heat exchanger (EAHE), as well as the place where the fresh air is cooled/heated. Thus an adequate knowledge of the temperature distribution of sub-soil is essential to study the heat transfer process of the air flowing through the EAHE system. Related studies indicate that the soil temperature follows a periodic sine function of time and depth, which experiences amplitude attenuates and phase delays with the increasing depth, but remains stable after reaching a certain depth[1,2]. It is these features of sub-soil that enable EAHE to cool/heat the fresh air.

Based on studies of soil temperature distribution, researchers have studied the thermal performance of EAHE theoretically, experimentally and numerically. Some of them have studied the heat transfer mechanism of EAHE system[3,4], and raised some analysis models and equations to evaluate its cooling capacity. Besides, other researchers devoted to clarifying the effect of parameters on the thermal performance of EAHE to improve its performance. Specifically, the parameters affecting the thermal performance of EAHE can be divided into geographical and meteorological conditions, like the condition of ground surface[5] and weather conditions[6]; Geometric parameters, like pipe length, buried depth and diameters[7], as well as the spacing in multi-tube arrangement[8]; Thermophysical properties, like soil type and moisture[9] and pipe material[10]; Operation strategies, like continuously or intermittently mode[11] and the air velocity[12].These studies indicate that the relationships between various parameters and EAHE's thermal performance have been sufficiently clarified, and the results are sufficient to guide the practical projects of EAHE.

However, all these EAHEs are single heat storage medium system, here the medium refers to the soil. For the purpose of differentiation, we define such systems as Traditional EAHE. It is generally known that a significant temperature change is inevitable during the charge/discharge process of the sensible heat storage medium. Thus, the Traditional EAHE, which has the soil as its sensible heat storage medium cannot fully exert its thermal performance in the narrow range of the daily temperature fluctuation. Due to large energy storage density and stable output temperature, latent heat storage technology has unparalleled advantages comparing to the sensible one. Therefore, the phase change material (PCM) is introduced into the Traditional EAHE to assist its cooling/heating process to overcome this deficiency. In particular, two assisted schemes are proposed, one is the hollow cylindrical PCM-assisted EAHE (HCPCM-EAHE)

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and the other is the cylindrical PCM-assisted EAHE(CPCM-EAHE). And to research the performance of them, a three-dimensional numerical model based on the effective heat capacity method will be established by FLUENT 16.0. Then, under the condition of equal air volume, these PCM-assisted EAHEs and a Traditional EAHE will be numerically studied to evaluate the cooling performance of these new systems under the meteorological conditions in Chongqing (China).

2 Numerical model

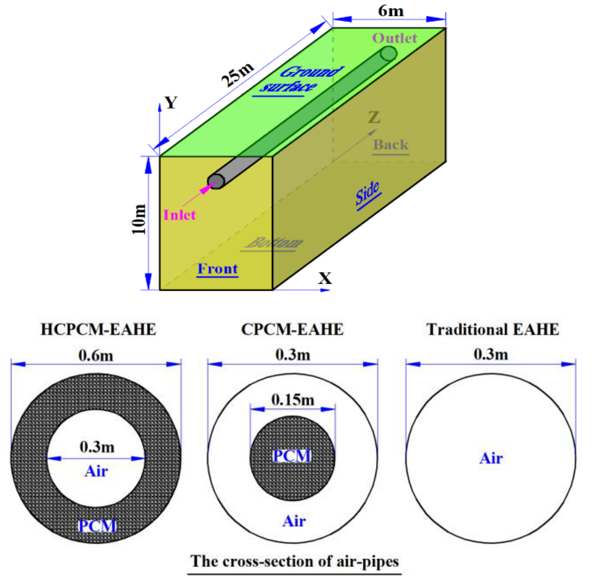

Fig.1 Schematic diagram and some key dimensions of HCPCM-EAHE, CPCM-EAHE and Traditional EAHE.

The schematic diagram and some key dimensions of the HCPCM-EAHE, CPCM-EAHE and Traditional EAHE are shown in Fig.1. And the following assumptions for these EAHE systems are made before conducting the practical research: (a). Air is incompressible and has constant thermophysical properties; (b). Soil is homogeneous and isotropic and its thermophysical properties are constant; (c). PCM is homogeneous and isotropic with its density and specific heat constant over the discussed temperature range; (d). The condensation and evaporation processes on all surface are all neglected; (e). The influence of contact thermal resistance, wall thickness of pipes, and the gravity are not in consider.

2.1 Governing equations

The three-dimensional numerical model for numerical simulating the cooling performance of the HCPCM-EAHE and CPCM-EAHE is established by Fluent 16.0. In this model, the turbulent process of air is resolved by the RNG $k-\varepsilon$ model. And the energy transfer process in this model is simulated by the equation as:

$$\rho C\left(\frac{\partial T}{\partial t}+u_j\frac{\partial T}{\partial x_j}\right)=\frac{\partial}{\partial x_j}\left(k\frac{\partial T}{\partial x_j}\right) \quad (1)$$

where, ρ is the density; C is the specific heat; T is the temperature; k is the thermal conductivity; $u_i$are velocity components; x_j are length components; t is the time.

In particular, the effective heat capacity method is conducted to resolve the phase transformation process of PCM. Since this method reasonably simplifies the phase transformation process to pure heat conduction problem by considering the latent heat of PCM as high sensible heat in a narrow range around the phase transformation temperature. The phase transformation temperature refers the peak temperature in phase transformation process. Thus the effective specific heat of PCM in phase transformation process is described as[13]:

$$C_{eff}=\begin{cases} C_1 & T<T_1 \\ \frac{C_1+C_2}{2}+f(T)\cdot L & T_1\le T\le T_2, \\ C_2 & T>T_2 \end{cases} \quad (2)$$

$$k_{pcm}=\begin{cases} k_1 & T<T_1 \\ k_1+\frac{k_2-k_1}{T_2-T_1}\cdot(T-T_1) & T_1\le T\le T_2 \\ k_2 & T>T_2 \end{cases} \quad (3)$$

where, C_{eff} is PCM's effective specific heat, and C_1, C_2 is PCM's specific heat before and after melting respectively; k_{pcm} is PCM's thermal conductivity, and k_1, $k_2$is PCM's thermal conductivity before and after melting respectively; L is the fusion heat; T_1, T_2 respectively represents the onset and end temperature.

2.2 Material properties

The phase transition parameters of the PCM and thermophysical properties of air and soil employed in this study are listed in Table 1. The effective heat capacity and thermal conductivity curves of the PCM are obtained according to the Equ. (2), as shown in Fig.2.

Table 1 Phase transition parameters of PCM.

Material	PCM	Air	Soil
Density ρ (kg/m^3)	904.5	1.165	1800
Thermal Conductivity k $(W/(m\cdot°C))$	5.43/3.26	0.0267	1.1
Specific heat C $(J/(kg\cdot°C))$	1750	1005	860
Fusion heat L (kJ/kg)	135.70		
Onset temperature (°C)	28.16		
Peak temperature (°C)	32.06		
End temperature (°C)	32.68		

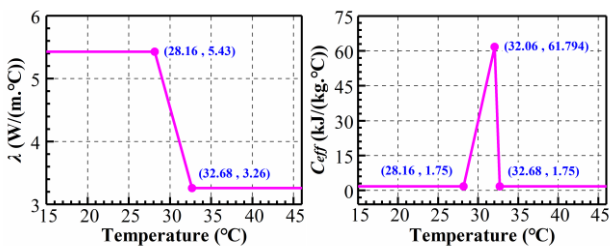

Fig.2 Effective heat capacity and thermal conductivity curves of the PCM.

2.3 Initial and boundary conditions

In this study, to calculate the sub-soil temperature at any depth and time, a theoretical equation[14] as follow is employed:

$$T(y,t)=T_{ms}+A_s exp\left(-y\sqrt{\pi/a_sT_y}\right)\times\cos\left(\omega_y t-\varphi_{y0}-y\sqrt{\pi/a_sT_y}\right) \quad (4)$$

where T_{ms} is the annual mean temperature of deep soil; A_s is the annual amplitude of temperature variation at the ground surface; φ_{y0} is the annual phase constant of the ground surface; a_s is the thermal diffusivity of soil. T_y is the annual period; and $\omega_y = 2\pi/T_y$ is the annual fluctuating frequency. For the TMY of Chongqing, these parameters are listed in Table 2. Additionally, the initial temperatures for the areas of PCM and air are all defined as 24.5℃.

Table 2. Parameters for defining the soil temperature of Chongqing.

Parameter	T_{ms}(°C)	A_s(°C)	φ_{y0}(rad)	a_s(m2/s)
Value	19.66	15.95	3.58	7.1×10-7

The detailed description of the boundary conditions employed in this study are list as follows:

(a) Inlet: the meteorological data from Jul-1 to Aug-9 in the TMY of Chongqing is employed as the temperature condition, as shown in Fig.3. In addition, the mean air velocity at this boundary are 2.0 m/s in HCPCM-EAHE and Traditional EAHE, and 2.67 m/s in CPCM-EAHE.

(b) Outlet: A fully developed flow condition, known as outflow, is appointed at this boundary.

(c) Ground surface: According to Ref.[15], the the hourly sol-air temperature of ground surface during the study period is calculated and drawn in Fig.3.

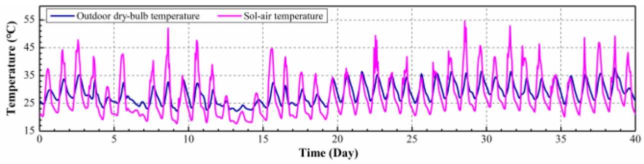

Fig.3 Hourly outdoor dry-bulb temperature and sol-air temperature from Jul-1 to Aug-9 in the TMY of Chongqing.

(d) Bottom: The calculation result of annual sub-soil temperature distribution in Chongqing indicates that the temperature fluctuation from the ground surface nearly disappears at the depth of 10 m. Thus, the temperature at this boundary is defined as 19.66 ℃, the annual mean temperature of deep soil in Chongqing.

(e) Front, Back and Sides: The sides are 3m from the pipe center, ten times of air pipe's diameter.Thus, the temperature distribution is considered undisturbed. And, the front and back are considered as adiabatic boundaries. That is to say, the boundary conditions at the front, back, and sides are: q = 0.

2.4 Validation and Solution setup

This model has been experimentally validated in our previous study on the PCM-assisted EAHE [15,16]. After comprehensive considering of boundary layer calculation and the computational efficiency, we finally employed structured meshes with sizes approximately 4 million as well as the Enhance Wall Treatment to study these EAHEs. Additionally, the SIMPLEC algorithm is applied in the pressure-based transient solver. A second-order upwind scheme is adopted for spatial discretization of the governing equations, and a second-order implicit scheme is chosen for setting the time-dependent solution formulation. The convergence criterion for energy is 10-8, whereas for others is 10^{-3}. After calculating this numerical model for different time-step sizes and comparing their results, a fixed time-step size of 60s is assigned to simulate these PCM-assisted EAHEs.

3 Results and discussion

After completing the simulation work, the hourly outlet air temperatures and cooling capacities of the HCPCM-EAHE, CPCM-EAHE and Traditional EAHE are obtained. Here, only the simulation results of day 19 to day 40, as shown in Fig.4, are employed to conduct the following discussions. Because the EAHE systems have experienced the examination of high-temperature weather for twenty sequentially days from the 20th day. Specially, the outlet air temperature and cooling capacity values are all time-average values.

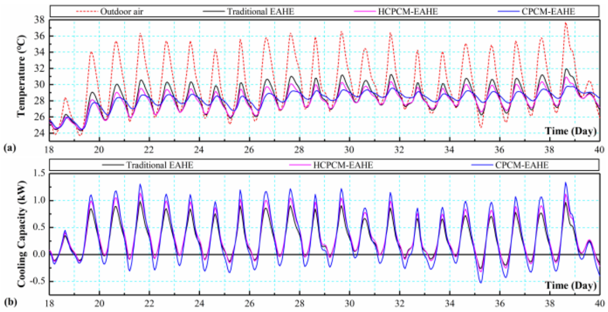

Fig.4 Hourly outlet air temperature and cooling capacity for different EAHEs. (a) Outlet air temperature; (b) Cooling capacity.

The Fig.4 indicates that these PCM-assisted EAHEs have great improvements on cooling performance when compared with the Traditional EAHE. Specifically, it is seen in Fig.4(a), during the daytime cooling period from day 20 to day 39, the outlet air temperatures of both HCPCM-EAHE and CPCM-EAHE are significantly lower than that of Traditional EAHE. And it is obvious that the CPCM-EAHE has the best efficiency on cooling the outdoor air. In terms of heat transfer, as shown in Fig.4(b), the PCM-assisted EAHEs have contributed more cooling capacities than Traditional EAHE during the daytime cooling period. In addition, these PCM-assisted EAHEs have released more heat in night, especially the CPCM-EAHE, which is very important to maintain the efficient operation of the system in the subsequent time.

It is seen in Fig.5(a), the changing trends of the daily average temperature of the outlet airflows in HCPCM-EAHE, CPCM-EAHE and Traditional EAHE are consistent, and the daily average temperatures are similar as well. However, Fig.5(b) shows that the daily amplitudes of outlet air temperature in these PCM-assisted EAHEs are remarkable lower than that in Traditional EAHE. And, in these novel systems, the amplitudes of the outlet air temperature of CPCM-EAHE is obviously smaller than the HCPCM-EAHE. In particular, the daily amplitudes of the outlet air temperature of CPCM-EAHE have been maintained within 1°C except for the 20th day.

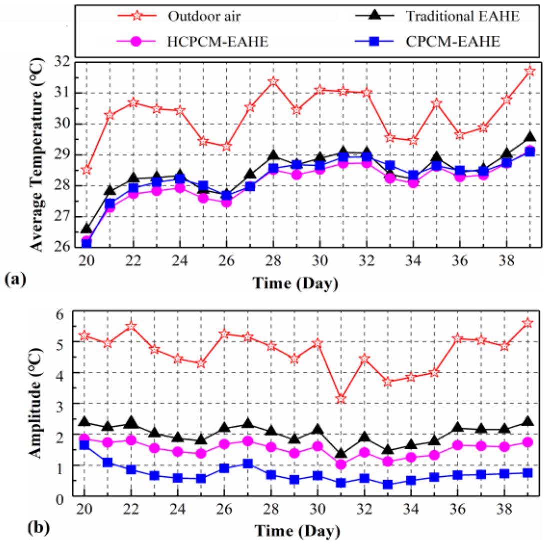

Fig.5 Daily average values and amplitudes of the outlet air temperature in different EAHEs during day 20 to day 39. (a) Daily average temperatures; (b) Daily amplitudes.

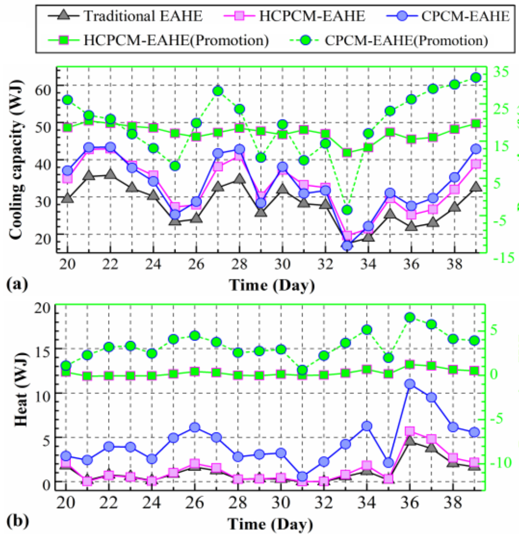

Fig.6 Daily total cooling capacities and Daily total heat releases of different EAHEs during day 20 to day 39. (a)Daily total cooling capacities; (b) Daily total heat releases.

Fig.6(a) shows that, when compared to the Traditional EAHE, the daily total cooling capacities of HCPCM-EAHE have been improved by 11.92% to 20.40%, and that of CPCM-EAHE have been improved by 8.36% to 32.12% (except the 33rd day) for the CPCM-EAHE. And in the studied 20 days, these improvements finally result in improvements of 17.68% and 20.05% in total contributed cooling capacity of the HCPCM-EAHE and CPCM-EAHE. In addition, the statistical results of total heat release for each day shown in Fig.6(b) demonstrate that the application of PCM in traditional EAHE has really promoted its heat release process. And the application model of the PCM has a significant impact on the level of promotion. It is obvious that the application mode of PCM in CPCM-EAHE is more helpful to promote the night heat release of the EAHE system. Which is conducive to the CPCM-EAHE to restore its cooling potential, as well as maintain its high efficient operation state.

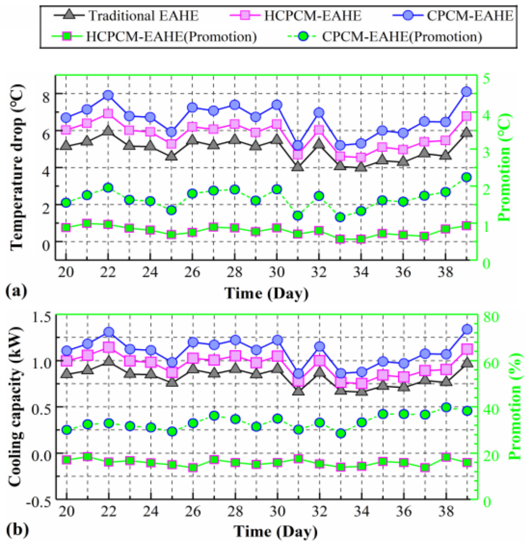

Fig.7 Temperature drops and cooling capacities of different EAHEs under the peak outdoor temperatures. (a) Temperature drops; (b) Cooling capacities.

Fig.7(a) shows that, under daily peak outdoor temperatures, the temperature drops of PCM-assisted EAHE are remarkable greater than that of Traditional EAHE, especially on the 39th day. When the temperature drop of the Traditional EAHE is only 5.86 ℃, the corresponding value of the HCPCM-EAHE is 6.79℃, an improvement of 0.93℃. In contrast, this value of CPCM-EAHE is as high as 8.10℃, an improvement of 2.24℃. Even in terms of the whole 20 days, the CPCM-EAHE still has an average improvement of 1.67℃. Additionally, Fig.7(b) indicates that the contributed cooling capacity of CPCM-EAHE under the peak outdoor temperature is greater than 1 kW in most days. In contrast, the Traditional EAHE can only contribute approximately 0.8 kW of cooling capacity under the same condition. Even at the 22nd and 29th days, its contributed cooling capacity is still no more than 1 kW. In addition, the contributed cooling capacities of the HCPCM-EAHE in these times are mainly between 0.9 to 1.0 kW. Overall, during the studied 20 days, the cooling capacity under the daily peak outdoor temperature has been increased by 13.64%~18.40% for HCPCM-EAHE, 28.55%~39.74% for CPCM-EAHE, when compared with the Traditional EAHE.

4 Conclusions

To enhance the cooling performance of the Traditional EAHE, this study proposed two PCM-assisted EAHEs, namely hollow cylindrical PCM-assisted EAHE and cylindrical PCM-assisted EAHE. The actual cooling performance of these PCM-assisted EAHE under the high-temperature meteorological conditions in Chongqing (China) has been numerically simulated by an effective heat capacity method based three-dimensional model on ANSYS Fluent 16.0. And the following conclusions can be conducted:

①The application of PCM in the Traditional EAHE truly enhanced the cooling performance of this passive cooling systems. Moreover, the application mode of PCM in CPCM-EAHE is better than that in HCPCM-EAHE.

②When the daily amplitude of outlet air temperature is concerned, the CPCM-EAHE has the best performance. Specifically, this amplitude in CPCM-EAHE has been nicely maintained within 1 °C.

③The total contributed cooling capacity of the studied 20 days is enhanced by 17.68% for the HCPCM-EAHE and 20.40 for the CPCM-EAHE when compared with the Traditional EAHE.

④The maximum temperature drops for the HCPCM-EAHE and the CPCM-EAHE are 6.79℃ and 8.10℃ respectively, while this value for the Traditional EAHE is 5.86℃. Such improvements result in an increase of cooling capacity under the daily peak outdoor temperature by 13.64%~18.40% for HCPCM-EAHE and by 28.55%~39.74% for CPCM-EAHE, when compared with the Traditional EAHE.

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